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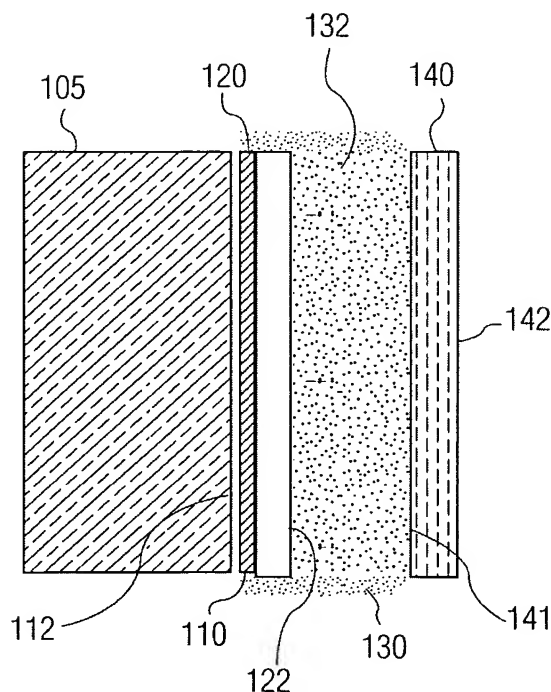
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(54) Title: PHOSPHOR-CONVERTED LED WITH LUMINANCE ENHANCEMENT THROUGH LIGHT RECYCLING

100



(57) Abstract: A light source (300) includes an LED chip (110) that emits light having a first central wavelength; a dichroic layer (120) on the LED chip (110), the dichroic layer (120) transmitting therethrough light having the first central wavelength, and reflecting light having a second central wavelength; a phosphor layer (130) on the dichroic layer (130) that converts light having the first central wavelength into light having the second central wavelength; an angular filter (140) on the phosphor layer (130) transmitting light within a transmission cone, and reflecting light outside the transmission cone; and a reflective polarizer (150) on the angular filter (140) transmitting light having a first polarization and reflecting light having a second polarization orthogonal to the first polarization.



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PHOSPHOR-CONVERTED LED WITH LUMINANCE ENHANCEMENT
THROUGH LIGHT RECYCLING

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This invention pertains to the field of light sources, and more particularly, to a phosphor-converted light emitting diode (LED) light source.

Light emitting diode (LED) light sources have many attributes that lend themselves
10 to illumination of non-emissive micro-displays for projection display systems. For example, LEDs can easily be intensity modulated and therefore are well suited to frame sequential color illumination schemes.

Unfortunately, however, an LED has limited intrinsic luminance (e.g., on the order of 10^6 cd/m²). In contrast, high pressure arc lamps have typical luminance values on the
15 order of 10^9 cd/m². The low intrinsic luminance of LEDs is viewed as a major barrier that prevents them from being used as light sources for large size projection displays.

U.S. patents 5,521,715 and 6,144,536, and H. Zou et al., "Required and Achievable Backlight Luminances for CRT-Replacement LCD Monitors," 28 SID SYMP 373 (1997) all describe a collimated illumination backlight scheme for direct view liquid crystal
20 displays (LCDs).

Accordingly, it would be desirable to provide an LED light source having enhanced effective brightness. It would also be desirable to provide such an LED light source which outputs light over a defined angular range. It would still further be desirable to provide such an LED light source producing linearly polarized light. The present invention is
25 directed to addressing one or more of the preceding concerns.

In one aspect of the invention, a light source comprises: a light emitting diode (LED) chip having a light emission surface and adapted to emit light having a first central wavelength, λ_1 ; a dichroic layer on the light emission surface of the LED chip, the dichroic layer transmitting therethrough light having the first central wavelength, λ_1 and reflecting
30 light having a second central wavelength, λ_2 ; a phosphor layer disposed on the dichroic layer adapted to convert the light having the first central wavelength, λ_1 into the light having the second central wavelength, λ_2 ; an angular filter disposed on the phosphor layer,

the angular filter transmitting light having an angle of no more than $\pm \alpha$ with respect to a normal to a light receiving surface of the angular filter, and reflecting light having an angle greater than $\pm \alpha$ with respect to a normal to a light receiving surface of the angular filter; and a reflective polarizer disposed on a light emission surface of the angular filter, the reflective polarizer being adapted to transmit light having a first polarization and to reflect light having a second polarization orthogonal to the first polarization.

In another aspect of the invention, a light source comprises: at least one light emitting diode (LED) having a light emission surface; a dichroic layer on the light emission surface of the light emitting diode; a phosphor layer disposed on the dichroic layer; and an angular filter disposed on the phosphor layer.

Further and other aspects will become evident from the description to follow.

FIG. 1 shows one embodiment of a phosphor-converted LED light source; FIG. 2 illustrates the angular-dependent transmission characteristics of an exemplary dichroic filter; FIG. 3 shows another embodiment of a phosphor-converted LED light source.

FIG. 1 shows one embodiment of a phosphor-converted LED light source 100. The light source 100 includes a light emitting diode (LED) chip 110, a dichroic layer 120 on the LED chip 110, a phosphor layer 130 disposed on the dichroic layer 120, and an angular filter 140 disposed on the phosphor layer 130. Optionally, the light source further includes a heat sink 105 on which the LED chip 110 is mounted.

Beneficially, the LED chip 110 includes one (or more) emitting LEDs having a first central wavelength, λ_1 . The LED chip 110 has a light emission surface 112. Similarly, the dichroic layer 120, phosphor layer 130, and angular filter 140 have corresponding light emission surfaces 122, 132 and 142. The angular filter also has a light receiving surface 141.

The phosphor layer 130 comprises a light conversion phosphor which absorbs light having the first central wavelength λ_1 , and emits light having a second central wavelength, λ_2 . Beneficially, $\lambda_2 > \lambda_1$. Also beneficially, the phosphor is a narrowband (e.g., 30 nm), long lifetime phosphor with a high quantum efficiency.

Also beneficially, the angular filter 140 comprises one of more dichroic filters, as discussed in more detail below. Alternatively, the angular filter 140 may comprise a transparent sheet having a prismatic array, for example, a VIKUITI™ Thin Brightness Enhancement Film (BEF) manufactured by 3M™ Corporation.

5 Operation of the light source 100 will now be provided. The LED chip 110 emits light having a first central wavelength, λ_1 , from its light emission surface 112.

The dichroic layer 120 receives the light from the LED chip having the first central wavelength, λ_1 and passes the light to the phosphor layer 130.

10 The phosphor in the phosphor layer 130 absorbs the light from the LED chip 110 having the first central wavelength λ_1 , and emits in all directions light having the second central wavelength, λ_2 . As shown in FIG. 1, some of the phosphor-converted light will be scattered toward the dichroic layer 120. The dichroic layer 120 is adapted to transmit therethrough light having the first central wavelength λ_1 , and to reflect light having the second central wavelength λ_2 . Accordingly, the phosphor-converted light that is scattered
15 toward the dichroic layer 120 will be reflected by the dichroic layer 120 toward the light emission surface 132 of the phosphor layer 130.

20 The angular filter 140 receives the phosphor converted light having the second central wavelength λ_2 from the emission surface of the phosphor layer 130. The angular filter 140 operates such that only light rays falling within a predefined incident cone (“transmission cone”) pass therethrough and are output from the light source 100 as an output light beam having a predefined cone angle. The remainder of the light, incident to the angular filter 140 at angles outside the transmission cone, is reflected by the angular filter 140 back into the phosphor layer 130. Advantageously, the angular filter 140 transmits light having an angle of no more than $\pm \alpha$ with respect to a normal to a light
25 receiving surface of the angular filter, and reflects light having an angle greater than $\pm \alpha$ with respect to a normal to a light receiving surface of the angular filter. Beneficially, α is about 20°.

30 The phosphor converted light rays reflected by the angular filter 140 is recycled in the phosphor layer 130 and again eventually redirected toward the emission surface with new, randomized angles. Hence, a fraction of this recycled light will now fall within the transmission cone of the angular filter 140. Recycling will occur multiple times until all of the light (except a small fraction that is absorbed in the recycle path) is eventually scattered

into the transmission cone of the angular filter 140 and therefore output from the light source 100 as part of the output light beam having the predefined cone angle.

Efficient recycling of light rejected by the angular filter 140 is facilitated because the recycled light is prevented by the dichroic layer 120 from entering the LED chip 110.

- 5 A primary function of the dichroic layer 120 is to maximize output from the LED chip of light having the first central wavelength λ_1 , and to minimize the possibility of light having the second central wavelength, λ_2 , from returning from the phosphor layer 130 to the LED chip 110.

- As noted above, the angular filter 140 beneficially comprises a dichroic filter. The
10 dichroic filter can be an edge filter whose cut-off wavelength, or transmission edge, shifts to shorter wavelengths as the light's angle of incidence increases with respect to a normal to the light receiving surface of the edge filter. In addition to edge filters, a band-pass filter can be used whose transmission window is matched to the wavelength of the phosphor-converted light. In that case, both the low and high cutoff wavelengths of the filter shift
15 with increasing angle of incidence.

The operation of a dichroic filter as an angular filter will now be explained with respect to FIG. 2.

- FIG. 2 illustrates the angular-dependent transmission characteristics of an exemplary dichroic filter. In particular, FIG. 2 shows the transmission characteristics
20 (transmission versus wavelength) for a cyan edge filter as a function of angle of incidence (angle between the light ray, and the normal to the light receiving surface of the filter). As can be seen, the cyan edge filter has the greatest bandwidth for light incident at an angle of 0° , where the filter exhibits a 50% transmission up to a wavelength of about 570 nm. As the angle of incidence increases from 0° to 50° , the 50% transmission bandwidth is reduced
25 from about 570 nm to about 520 nm.

- Accordingly, if the phosphor layer 130 is adapted to emit light having a second central wavelength, λ_2 , of about 560 nm, it is seen that over 80% of the light from the phosphor layer incident to the cyan edge filter at an angle of 0° passes through the cyan edge filter. In contrast, only about 20% of the light from the phosphor layer incident to the
30 cyan edge filter at an angle of about 30° passes through the cyan edge filter and the bulk of the light is instead reflected back to the phosphor layer 130. Meanwhile, the incidence angle where about 50% of the light from the phosphor layer passes through the cyan edge

filter is about 20°. Accordingly, when λ_2 is about 560 nm, the transmission cone of an angular filter 140 comprising the cyan edge filter of FIG. 2 is about $\pm 20^\circ$.

The light source 100 can provide efficient recycling of light by avoiding the high internal absorption of the LED chip 110, since the recycled light is prevented by the dichroic layer 120 from entering the LED chip 110 and is instead scattered by the phosphor layer 130 which is typically highly reflective and has very little internal absorption. Meanwhile, the phosphor layer 130 also provides effective angular scrambling of light rays reflected by the angular filter 140. The result is an output light beam with a defined angular distribution from a light source with a low physical profile package.

Furthermore, the arrangement above can provide a significant luminance enhancement over the intrinsic luminance of the bare LED chip 110 by itself. The relationship between effective luminance and intrinsic luminance is shown in Equation 1 as:

$$1) \quad L_{\text{effective}} = L_{\text{intrinsic}} \sum_{n=0}^{\infty} f^n = \frac{L_{\text{intrinsic}}}{1-f}$$

where f is the fraction of the light that is fed back into the light source for recycling.

For example, for a defined angular light distribution of $\pm 20^\circ$, the achievable luminance enhancement of a bare LED chip (having a reflectivity of 60%) is only about a factor of 2:1. However, in the light source 100, the achievable luminance enhancement (with total reflectivity of 95%) can be as high as 6.2:1. In both cases, a Lambertian distribution is assumed for the initial radiation from the LED chip and the phosphor layer.

In some applications, such as a light source for illumination a liquid crystal display (LCD) (for example, a liquid crystal on silicon (LCOS) device), it is important that the light source produce linearly polarized light.

In that case, FIG. 3 shows another embodiment of a phosphor-converted LED light source 300 that outputs polarized light. The light source 300 includes a light emitting diode (LED) chip 110, a dichroic layer 120 on the LED chip 110, a phosphor layer 130 disposed on the dichroic layer 120, an angular filter 140 disposed on the phosphor layer 130, and a reflective polarizer 150. Optionally, the light source further includes a heat sink 105 on which the LED chip 110 is mounted.

The components and operation of the light source 300, other than the reflective polarizer 150 and the linear polarization process, are the same as those of the light source 100 and so the description thereof will not be repeated here. The reflective polarizer 150 may comprise a transparent sheet having a multi-layered coating, for example, a
5 VIKUITI™ Dual Brightness Enhancement Film (DBEF) manufactured by 3M™ Corporation. Alternatively and beneficially, the reflective polarizer 150 can comprise a wire grid polarizer.

In the light source 300, light passing through the transmission cone of the angular filter 140 is then provided to the reflective polarizer 150. The reflective polarizer 150
10 transmits only that portion of the received light polarized in one direction, and reflects light polarized in the other, orthogonal direction.

Accordingly, in addition to the benefits of the light source 100 mentioned above, in the light source 300 the phosphor layer 130 also provides effective polarization scrambling of light rays reflected by the reflective polarizer 150. The result is an output light beam
15 with a defined angular distribution and polarization state from a light source with a low physical profile package.

While preferred embodiments are disclosed herein, many variations are possible which remain within the concept and scope of the invention. Such variations would become clear to one of ordinary skill in the art after inspection of the specification;
20 drawings and claims herein. The invention therefore is not to be restricted except within the spirit and scope of the appended claims.

CLAIMS:

1. A light source (300), comprising:
 - a light emitting diode (LED) (110) chip having a light emission surface (112) and adapted to emit light having a first central wavelength, λ_1 ;
 - a dichroic layer (120) on the light emission surface of the LED chip (110), the dichroic layer (120) transmitting therethrough light having the first central wavelength, λ_1 and reflecting light having a second central wavelength, λ_2 ;
 - a phosphor layer (130) disposed on the dichroic layer (120) and adapted to convert the light having the first central wavelength, λ_1 into the light having the second central wavelength, λ_2 ;
 - an angular filter (140) disposed on the phosphor layer (130), the angular filter (140) transmitting light having an angle of no more than $\pm \alpha$ with respect to a normal to a light receiving surface (141) of the angular filter (140), and reflecting light having an angle greater than $\pm \alpha$ with respect to a normal to a light receiving surface (141) of the angular filter (140); and
 - a reflective polarizer (150) disposed on a light emission surface (142) of the angular filter (140), the reflective polarizer (150) being adapted to transmit light having a first polarization and to reflect light having a second polarization orthogonal to the first polarization.
2. The light source (300) of claim 1, wherein α is 20° .
3. The light source (300) of claim 1, wherein the angular filter (140) includes at least one dichroic filter.
4. The light source (300) of claim 1, wherein the angular filter (140) includes a transparent sheet having a prismatic array.
5. The light source (300) of claim 1, wherein the reflective polarizer (140) comprises a wire grid.

6. The light source (300) of claim 1, wherein the reflective polarizer (140) comprises a transparent sheet having a multi-layer coating.
7. A light source (100, 300), comprising:
at least one light emitting diode (LED) (110) having a light emission surface (112);
a dichroic layer (120) on the light emission surface (112) of the LED (110);
a phosphor layer (130) disposed on the dichroic layer (120); and
an angular filter (140) disposed on the phosphor layer (130).
8. The light source (300) of claim 6, further comprising a wire grid disposed on the angular filter (140).
9. The light source (300) of claim 6, further comprising a transparent sheet having a multi-layer coating disposed on the angular filter (140).
10. The light source (100, 300) of claim 6, wherein the angular filter (140) comprises a transparent sheet having a prismatic array.
11. The light source (100, 300) of claim 6, wherein the angular filter (140) includes a dichroic filter.
12. The light source of claim 6, wherein the angular filter (140) transmits light having an angle of no more than $\pm 20^\circ$ with respect to a normal to a light receiving surface (141) of the angular filter (140), and reflecting light having an angle greater than $\pm 20^\circ$ with respect to a normal to a light receiving surface (141) of the angular filter (140).

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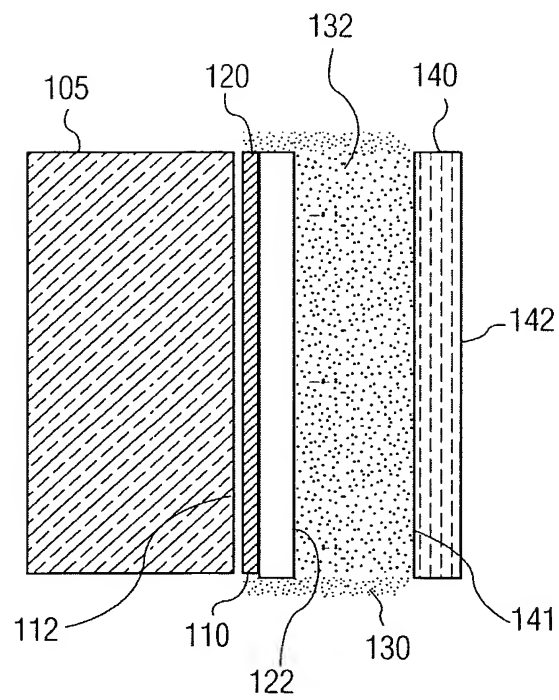
100

FIG. 1

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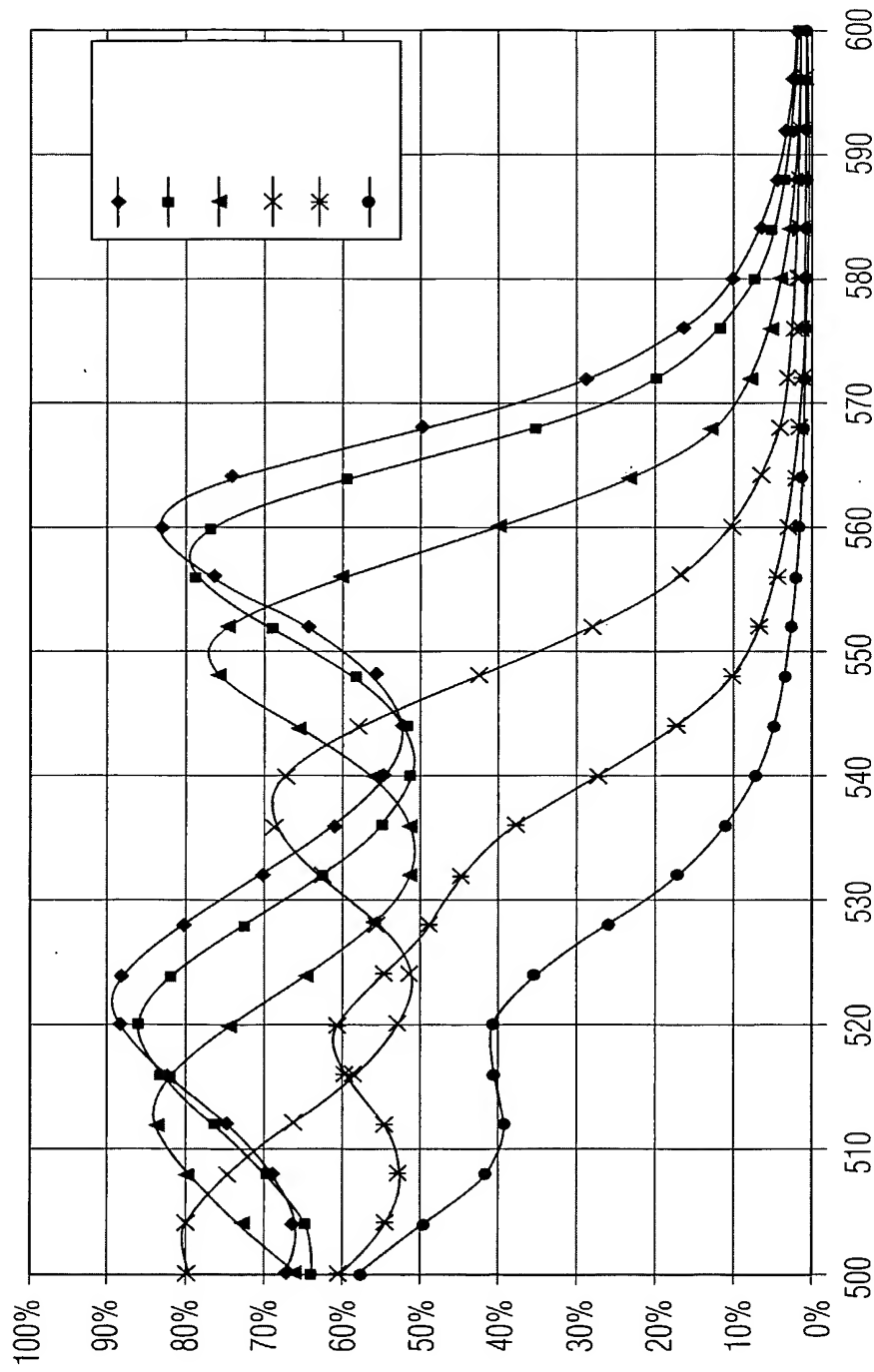


FIG. 2

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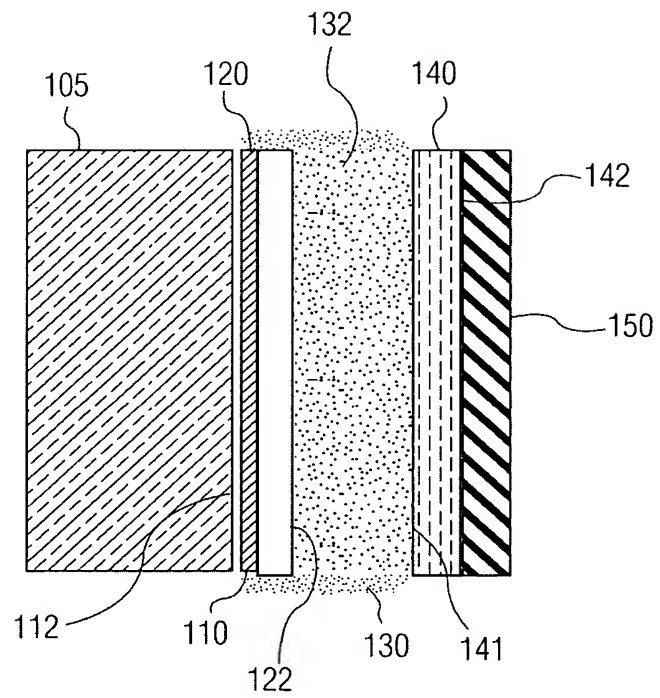
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FIG. 3

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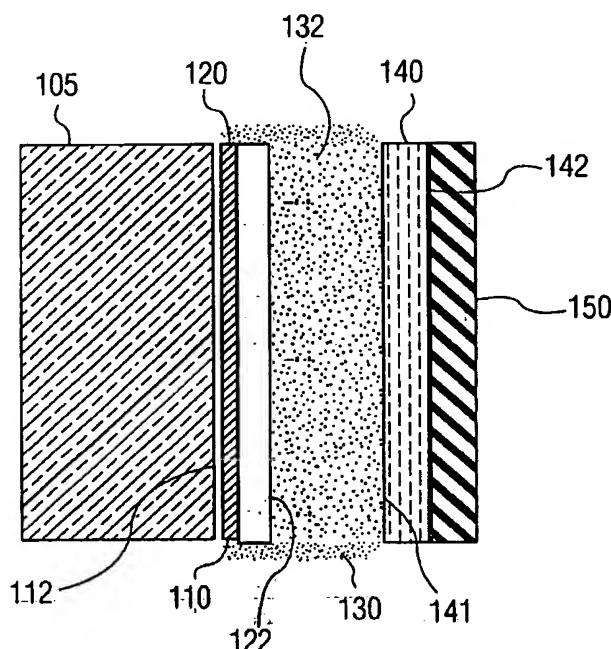
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(54) Title: PHOSPHOR-CONVERTED LED WITH LUMINANCE ENHANCEMENT THROUGH LIGHT RECYCLING

300



(57) Abstract: A light source (300) includes an LED chip (110) that emits light having a first central wavelength; a dichroic layer (120) on the LED chip (110), the dichroic layer (120) transmitting therethrough light having the first central wavelength, and reflecting light having a second central wavelength; a phosphor layer (130) on the dichroic layer (120) that converts light having the first central wavelength into light having the second central wavelength; an angular filter (140) on the phosphor layer (130) transmitting light within a transmission cone, and reflecting light outside the transmission cone; and a reflective polarizer (150) on the angular filter (140) transmitting light having a first polarization and reflecting light having a second polarization orthogonal to the first polarization.

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B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.



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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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